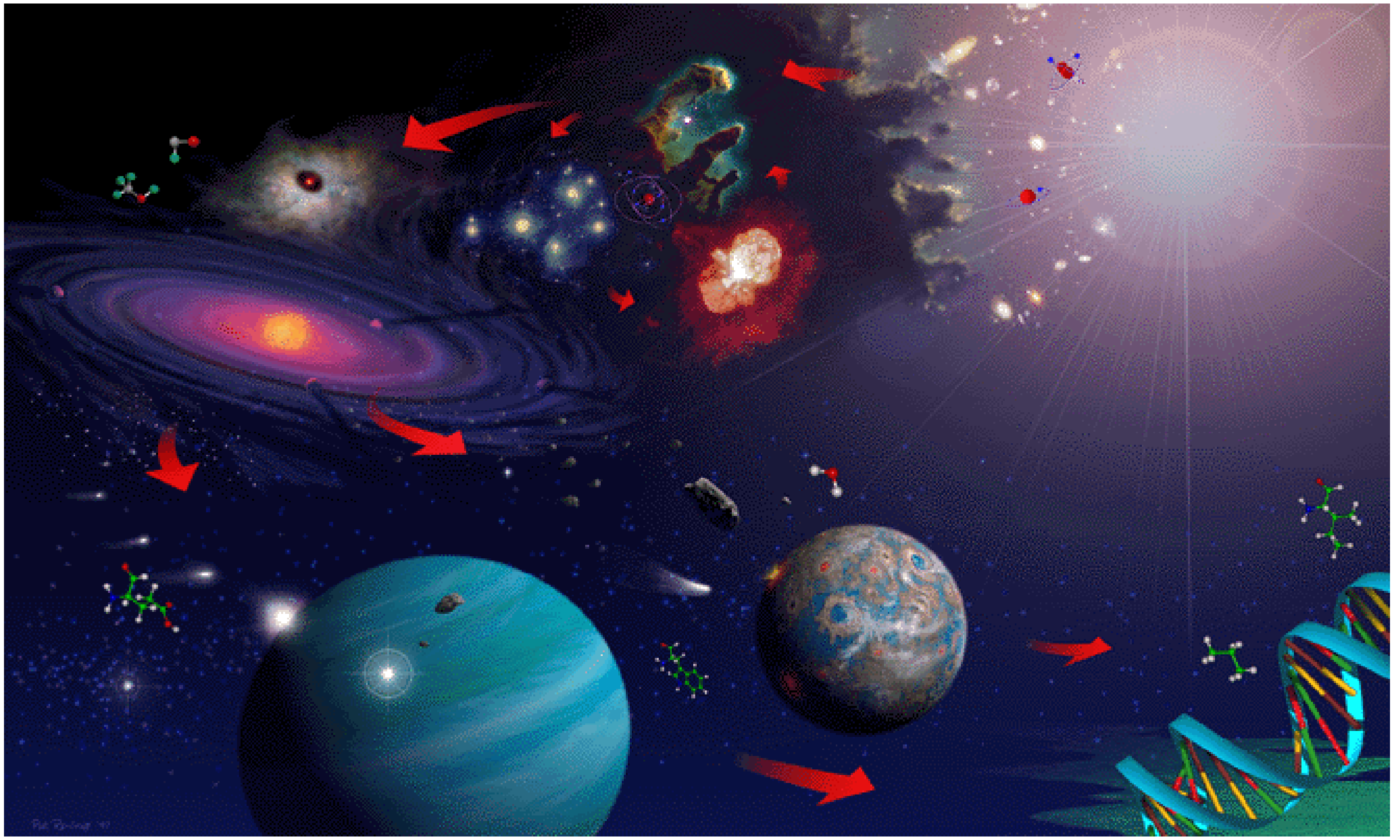
NASA's Terrestrial Planet Finder: The Search for (Habitable) Planets



C. Beichman, JPL

From Greek Philosophers ...

"There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and planets and other things we see in this world."

Epicurius (c. 300 B.C)

…and Medieval Scholars...

"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth"

Giordano Bruno (1584)
in De L'infinito Universo E Mondi

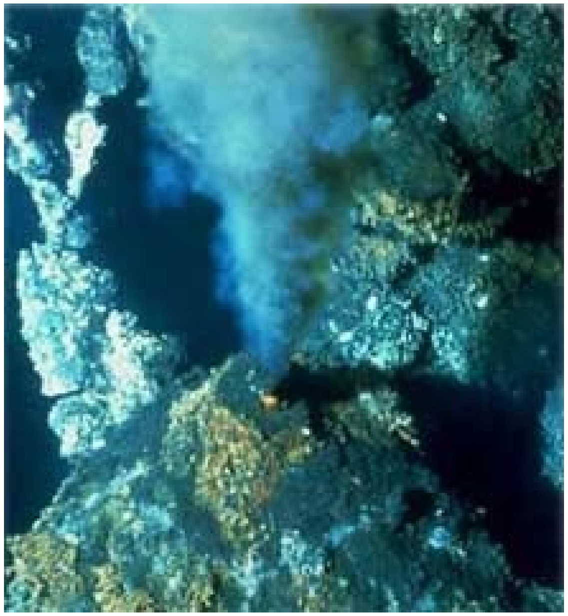
...To Hollywood Producers...

We *have looked for life beyond the Earth, but now we can use science for this search*

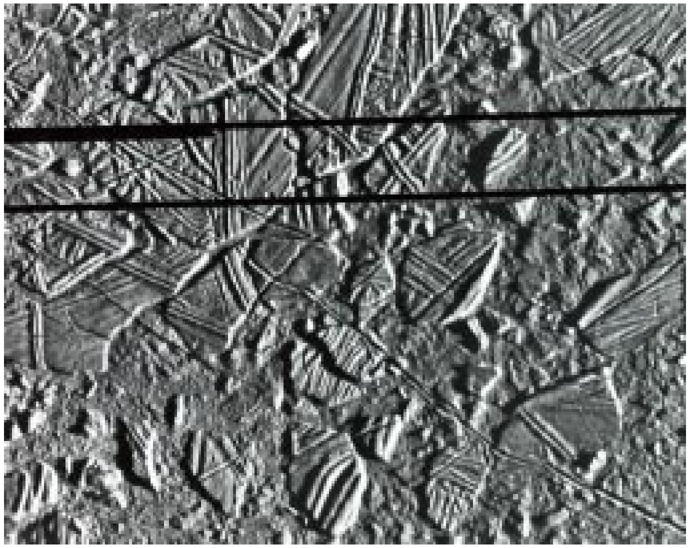
NASA's Astronomical Search for Origins

- To understand how galaxies formed in the early universe and to determine the role of galaxies in the appearance of stars, planetary systems and life.
  - *What is the history and evolution of the heavy elements that make life possible?*
- To understand how stars and planetary systems form and to determine whether life-sustaining planets exist around other stars.
  - *Where are our planetary neighbors beyond the solar system?*
- To understand how life originated on Earth and to determine if it began and may still exist elsewhere as well.
  - *What are essential and accidental properties of Earth as abode for life?*

Search for Life in 3 Locales



- Origins Program is part of a broad-based search for life
  - Reflects advances in understanding physical, chemical, genetic basis of life on Earth
- Life in Extreme Environments on Earth
  - Undersea volcanic vents, frozen Antarctic lakes, Atacama desert in Chile
- Life in the solar system
  - Comets, Mars and Europa using landers, flybys and sample return
- Life beyond the solar system
  - Search for habitable, or even inhabited, Earth-like planets



Some Fundamental Things to Remember

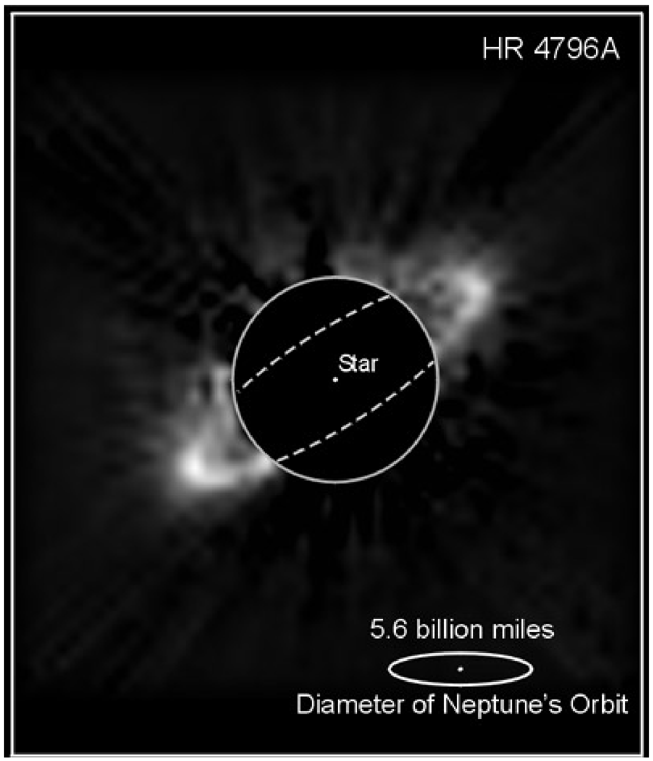
- Planets are a common outcome of the formation of solar type stars
- The necessary ingredients of life (as we know it) are widespread
- Life on Earth is hardy and inhabits harsh niches
- Life can affect a planetary environment enough to be detected from many light years away with technology soon to be in hand

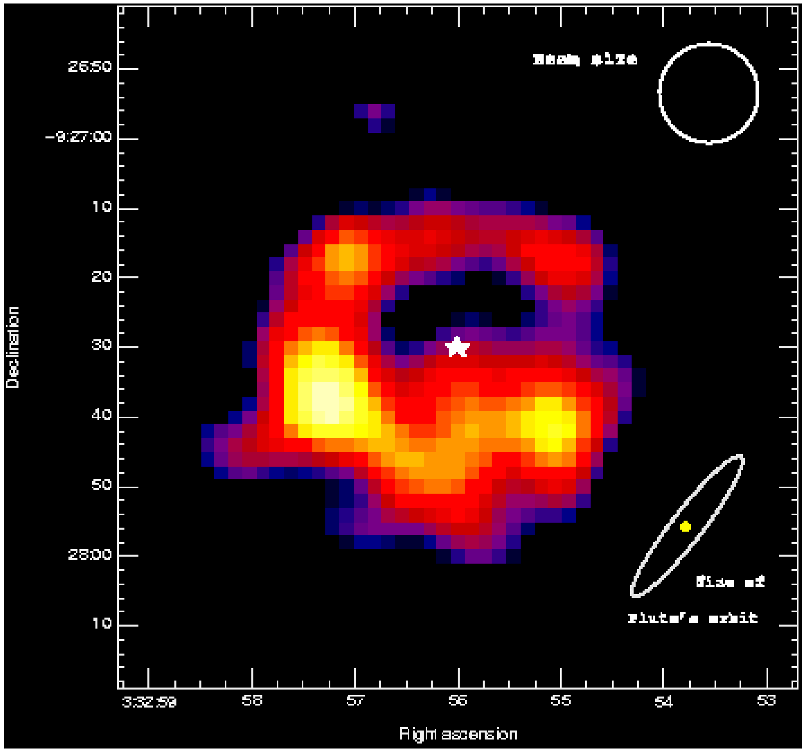
Star Formation in Orion

- Hundreds of protostars forming our of gas clouds
  - *Many with evidence for disks*

Star Formation & Protoplanetary Disks

- The formation of planets is an integral part of our theory of how stars form
  – Dust disks the same size as our own solar system found around nearby stars

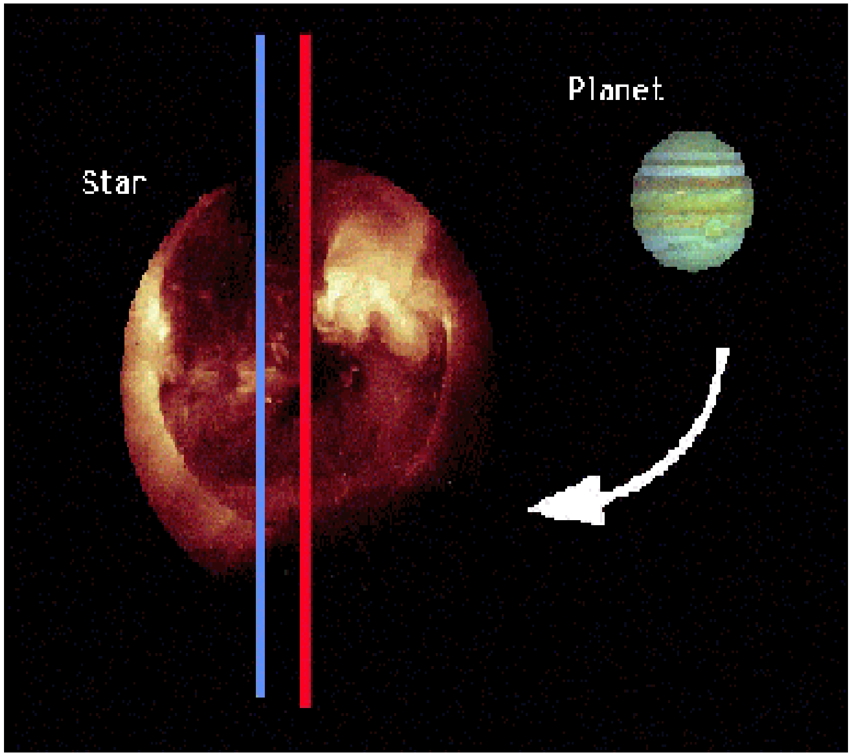




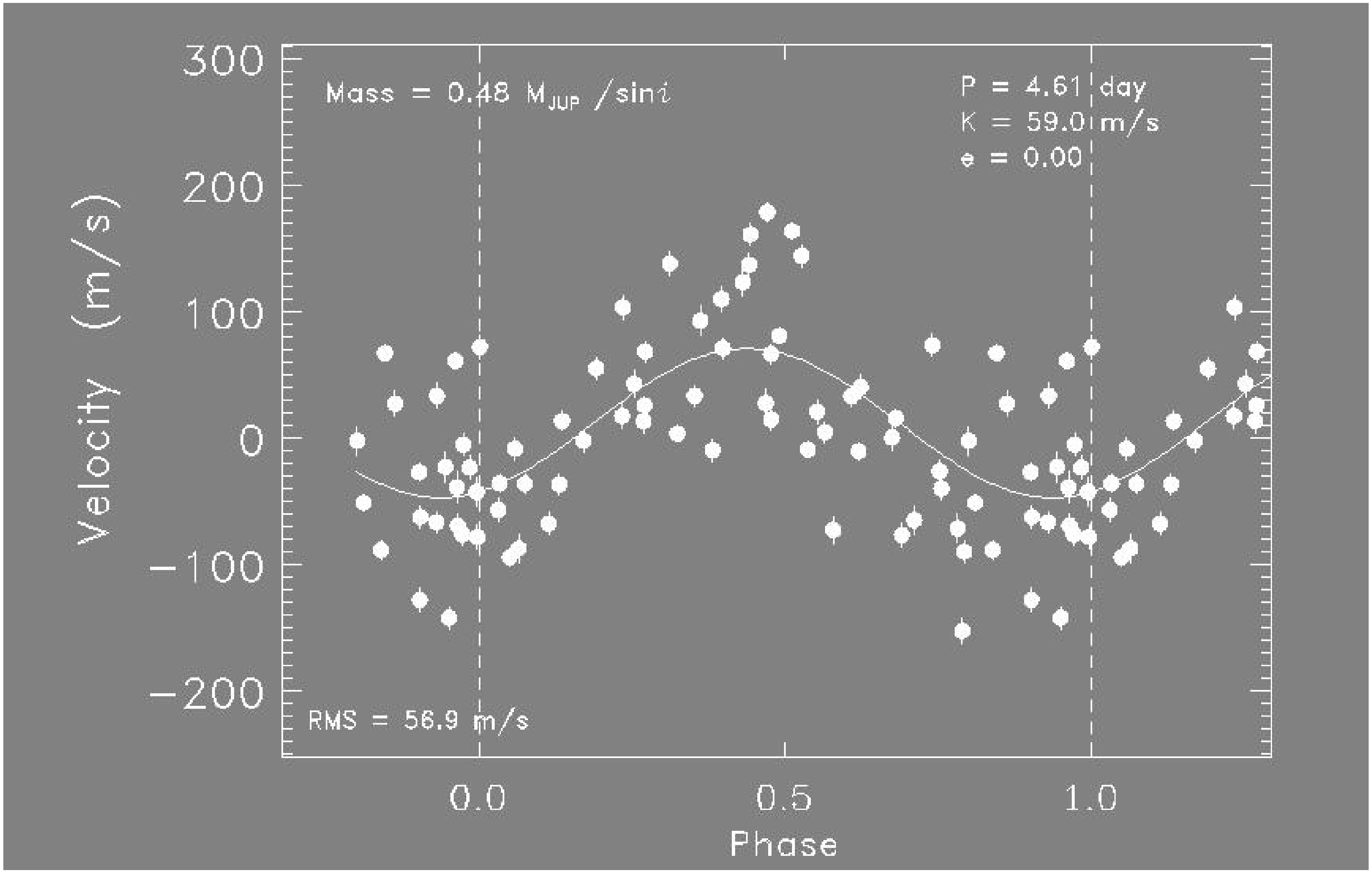
Finding Planets Indirectly

- Gravitational Effects on Parent Star
  - Radial Velocity Changes
    - Favors large planets in close to star
    - Independent of distance
  - Positional Wobble (Astrometry)
    - Favors large planets far from star
    - Angular displacement decreases with distance
- Effect of Planet on Star's Brightness
  - Occultation
  - Gravitational Lensing
    - Large samples of distant stars

→ Learn about planet's mass, radius & orbital distance. Nothing about composition.

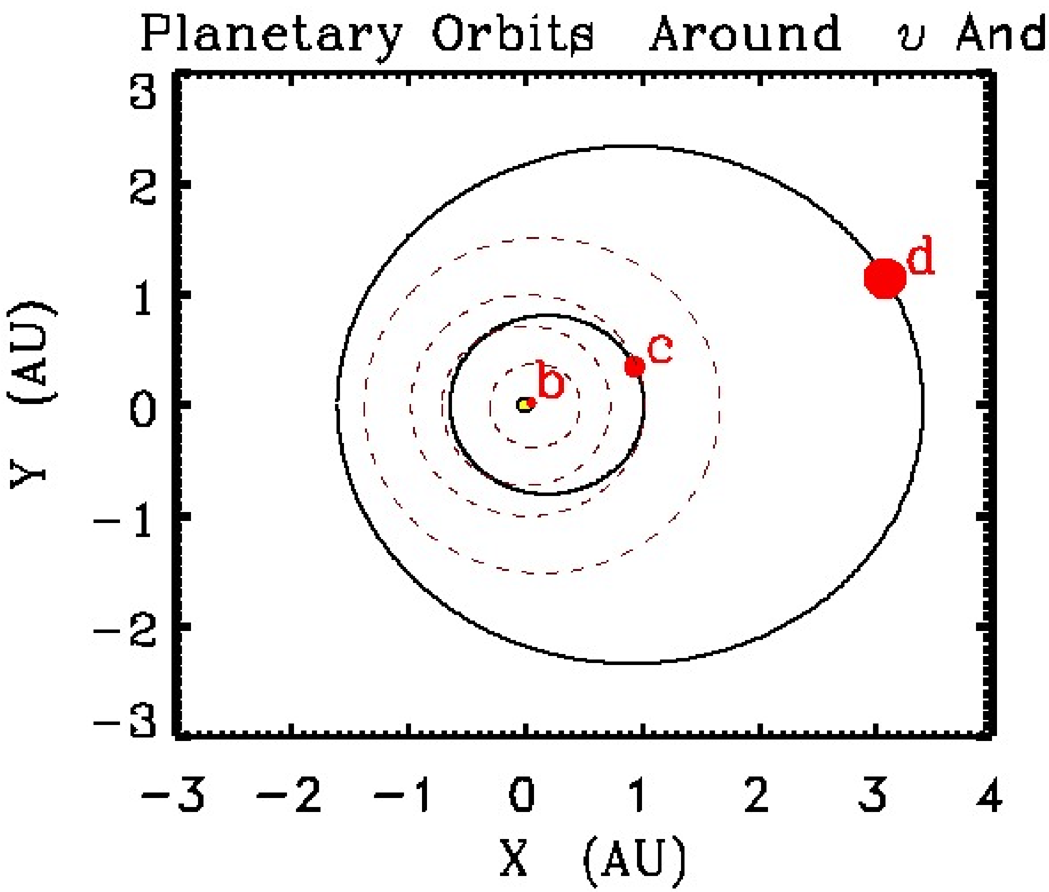


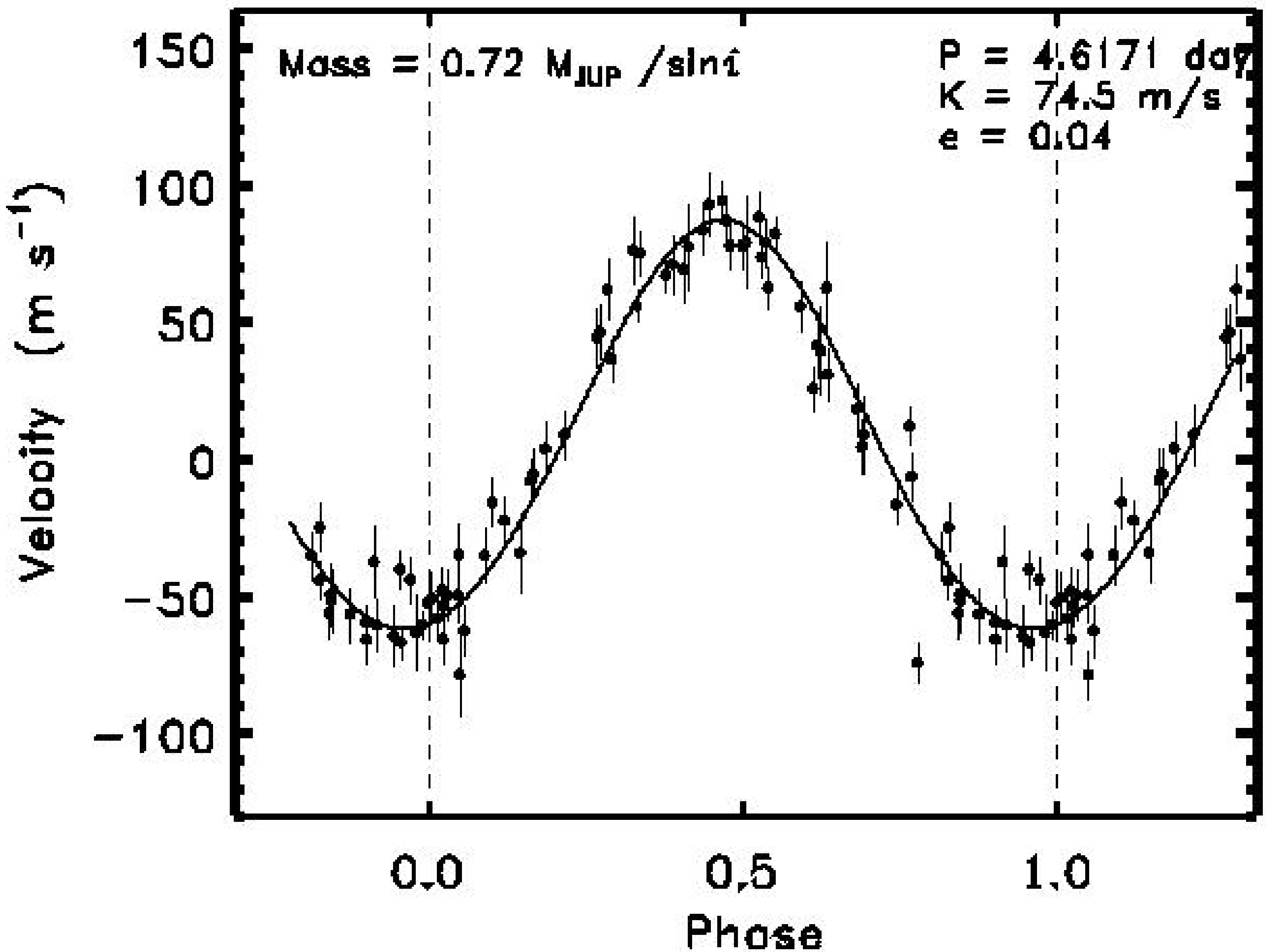
Radial Velocity Searches (Marcy et al.)



A Planetary System Around the Star Ups Andromedae

Planet	Mass* sin(I) $M_{Jupiter}$	Orbit (AU)	Temp (deg F)
B	0.73	0.06	1800
C	1.95	0.85	62 to 135
D	4.1	2.5	-113 to -182



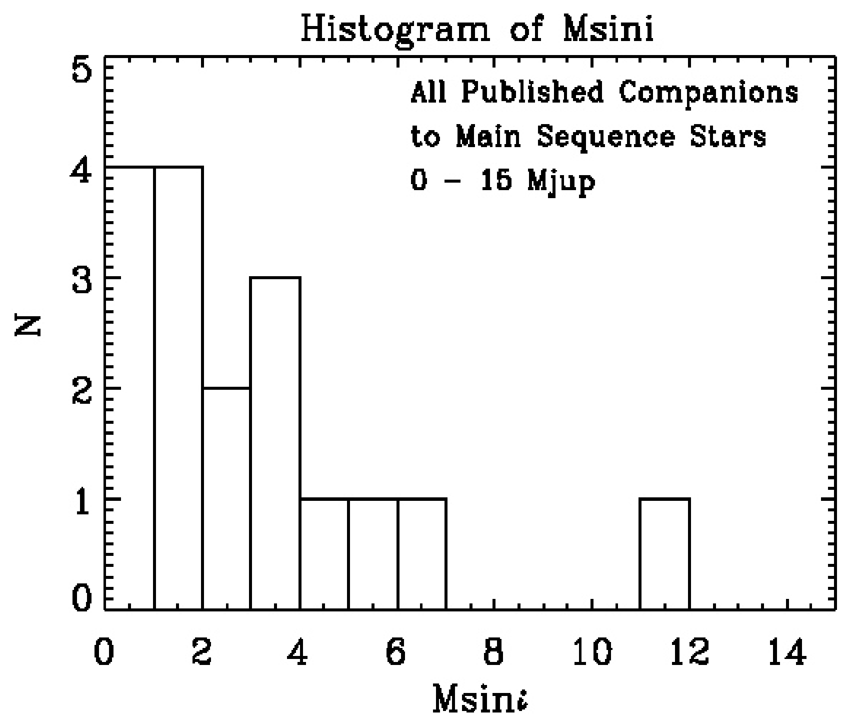


Mass = 0.72 M_JUP /sini
P = 4.6171 day
K = 74.5 m/s
e = 0.04
Velocity (m s^-1)
150
100
50
0
−50
−100
0.0
0.5
1.0
Phase

Planet Census from Radial Velocities (Marcy et al.)

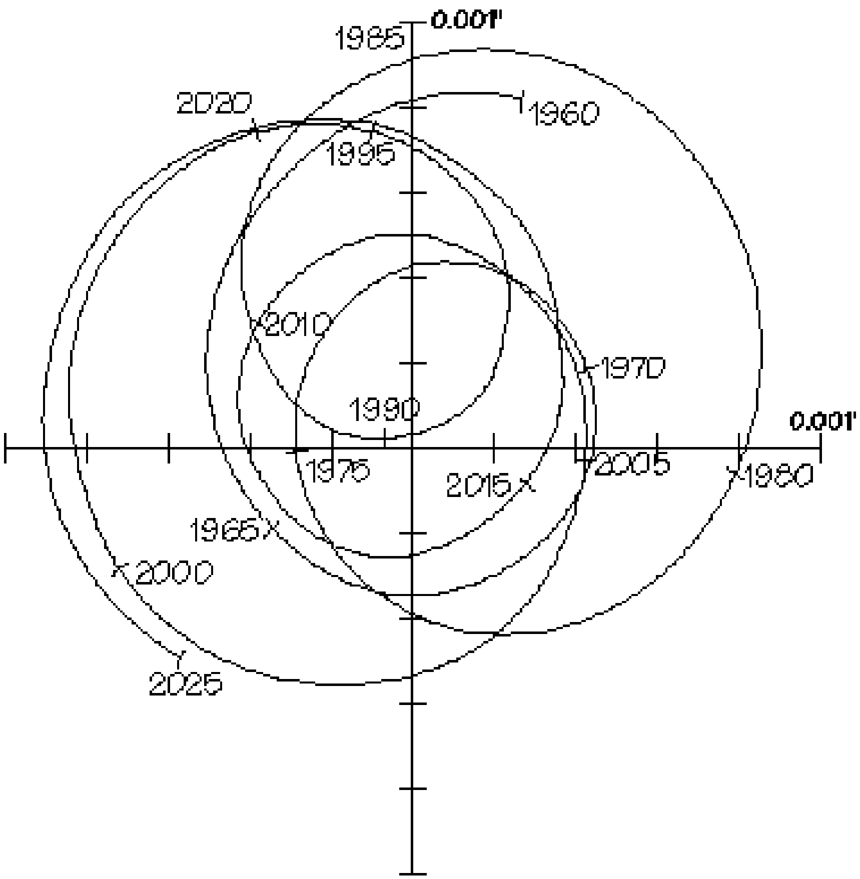
Properties of Planets found via Radial Velocity Technique

- Planets found have Msin(i)~ 0.5-15 $M_{Jupiter}$
- Most planets found closer to star than expected from theory of formation of gas giants
  - Bias of radial velocity technique
  - Migration theories might account for close distances
- Broad range of orbital properties (eccentricity,etc)
- Brown dwarf of planet?
  - At least one system (υ And) → planets

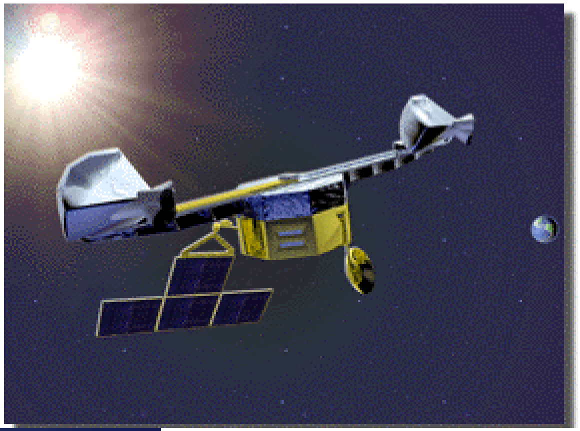


Astrometric Search for Planets

- Astrometry measures positional wobble due to planets
  - More sensitive than RV
  - no sin(i) ambiguity
- New technique of interferometry will enable measurements at the micro-arcsecond level
  - Earth at 10 pc produces 0.3 μas amplitude
- Result of new observing systems will be a census of planets down to a few M_{earth} over the next 10-20 years



NASA’s First Interferometers

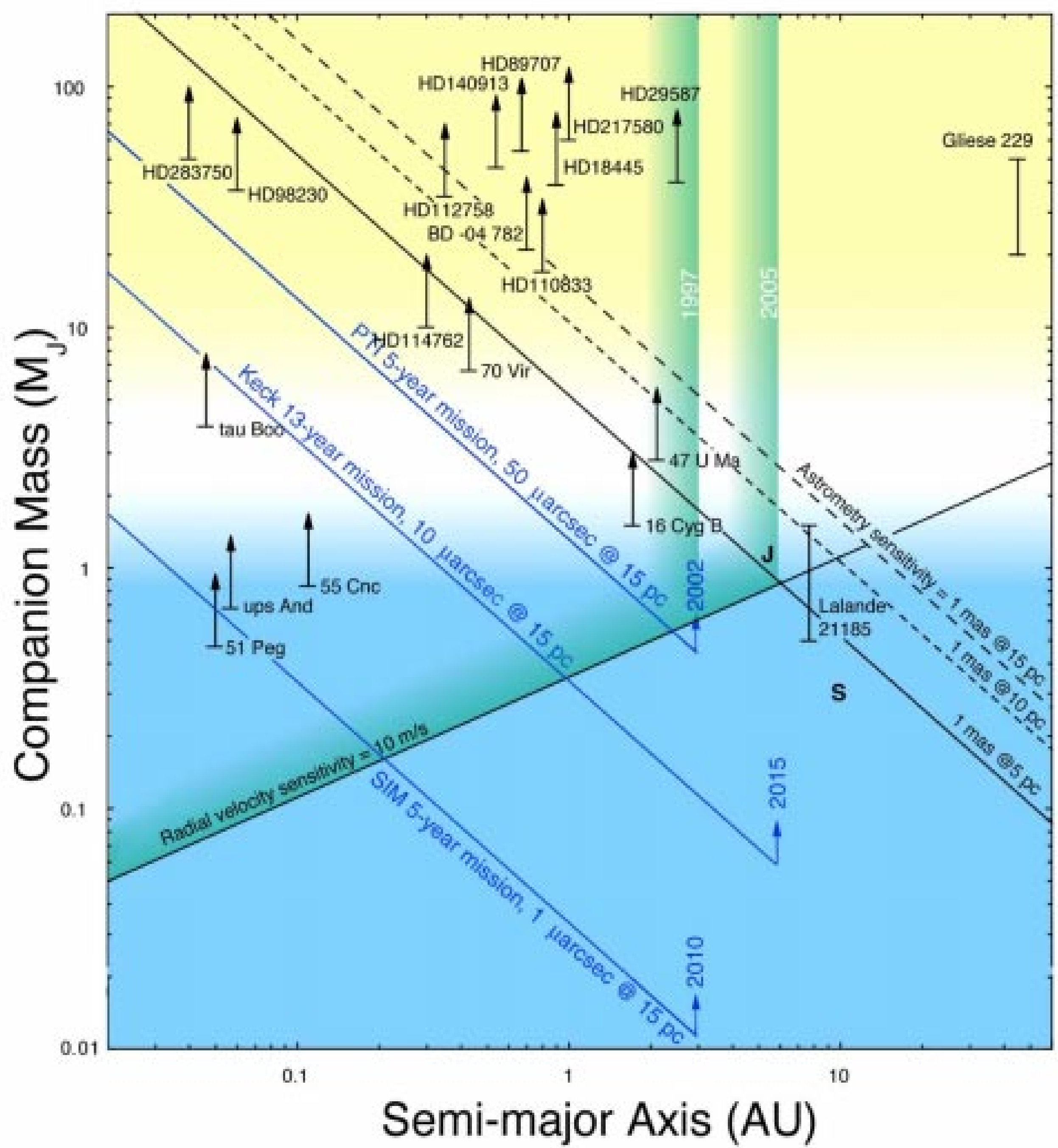


• Palomar Testbed
• Keck Interferometer
• Space Interferometer Mission (SIM)

• Develop interferometer technology
• Detect Hot Jupiter’s
•Detect exo-zodiacal dust clouds
•Make astrometric census of planets

Space Interferometer Mission

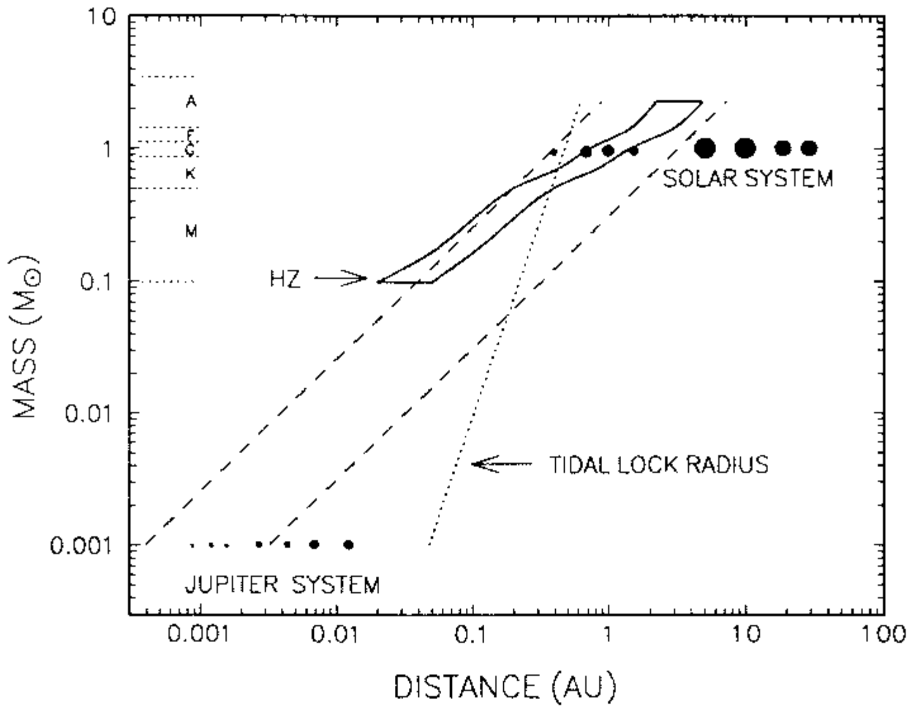
- Advances state of art by x1,000 in accuracy and faintness
  - Global Astrometry with 4 μas accuracy
  - Differential Astrometry with 1 μas accuracy
  - Operate on objects as faint as R~ 20 mag
- SIM will be first optical interferometer in space
  - Breaks link between baseline (resolution $\propto \lambda/B$) and collecting area ($\propto D^2$)
- Daunting technical challenges
  - Nanometer control with picometer knowledge
- SIM will provide census of planets and a catalog for future studies
  - Jupiter-mass to 1 kpc
  - Few Earth-mass to 5 pc



Companion Mass (M_J)
Semi-major Axis (AU)
HD89707
HD140913
HD29587
HD217580
HD18445
HD283750
HD98230
HD112758
BD -04 782
HD110833
Gliese 229
HD114762
70 Vir
tau Boo
47 U Ma
16 Cyg B
55 Cnc
ups And
51 Peg
Lalande 21185
J
S
1997
2005
2002
2015
2010
PTI 5-year mission, 50 μarcsec @ 15 pc
Keck 13-year mission, 10 μarcsec @ 15 pc
SIM 5-year mission, 1 μarcsec @ 15 pc
Radial velocity sensitivity = 10 m/s
Astrometry sensitivity = 1 mas @15 pc
1 mas @10 pc
1 mas @5 pc

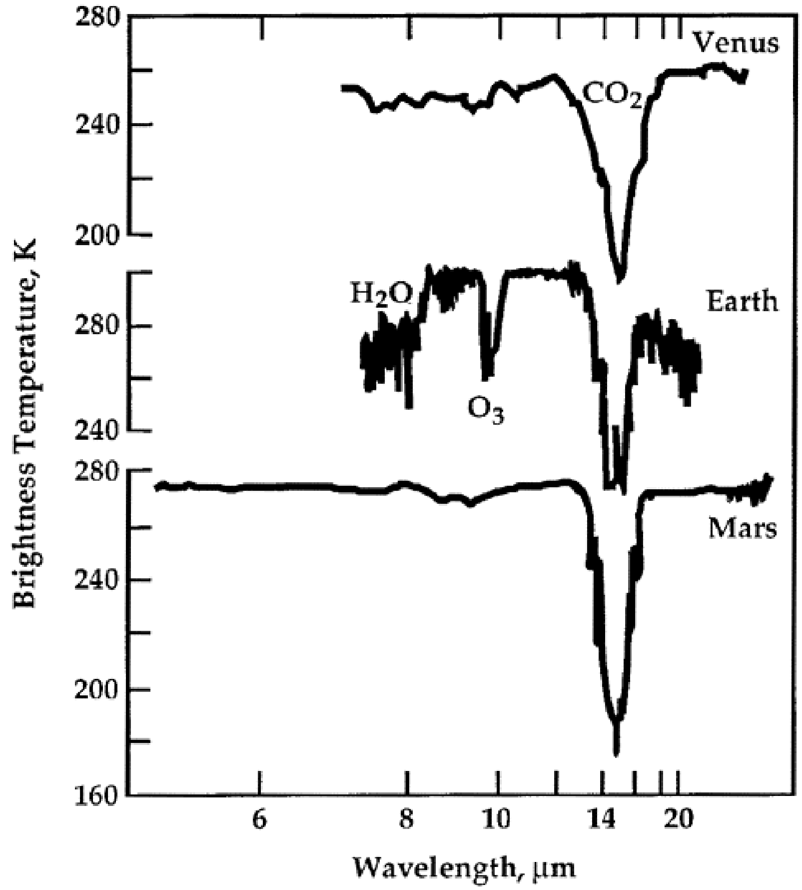
But What is a Habitable Planet?

- Not too **big**
  - Avoid accreting material to become gas giant
- Not too small
  - Lose atmosphere
- Not too hot or too cold
  - No liquid water
- Not too close to star
  - Avoid tidal lock
- Moons like Europa also possible abodes for life



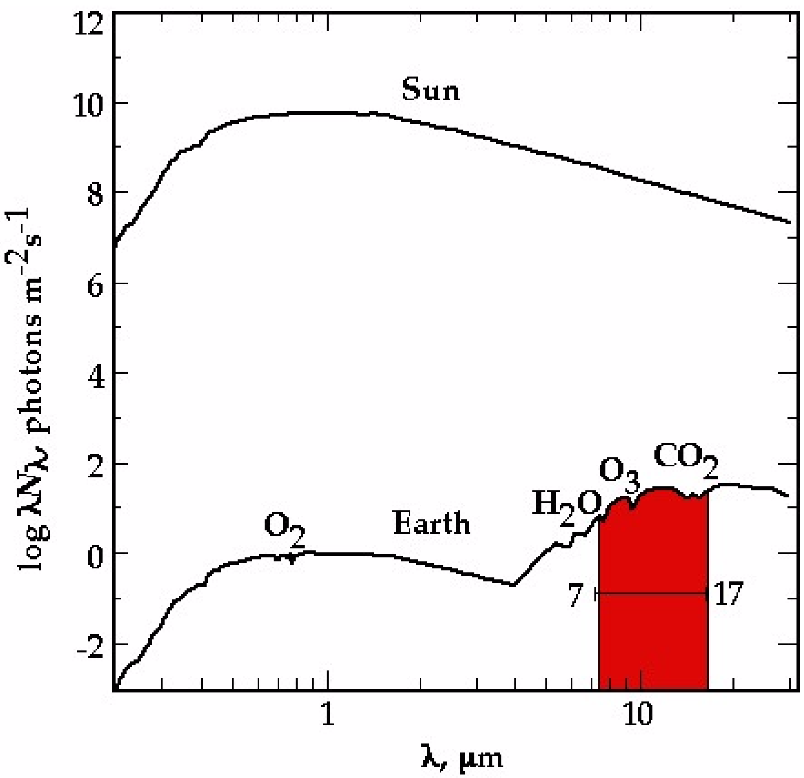
What Are Signposts of Habitability & Life?

- Find an atmosphere (CO_2)
- Find a warm, wet atmosphere (H_2O)
- Find an atmosphere out of chemical equilibrium
  - Global presence of life can modify atmosphere producing $O_2 \rightarrow O_3$, CH_4, N_2O (Lovelock, Sagan, Margulis)
- Mid-IR spectroscopy can identify trace species



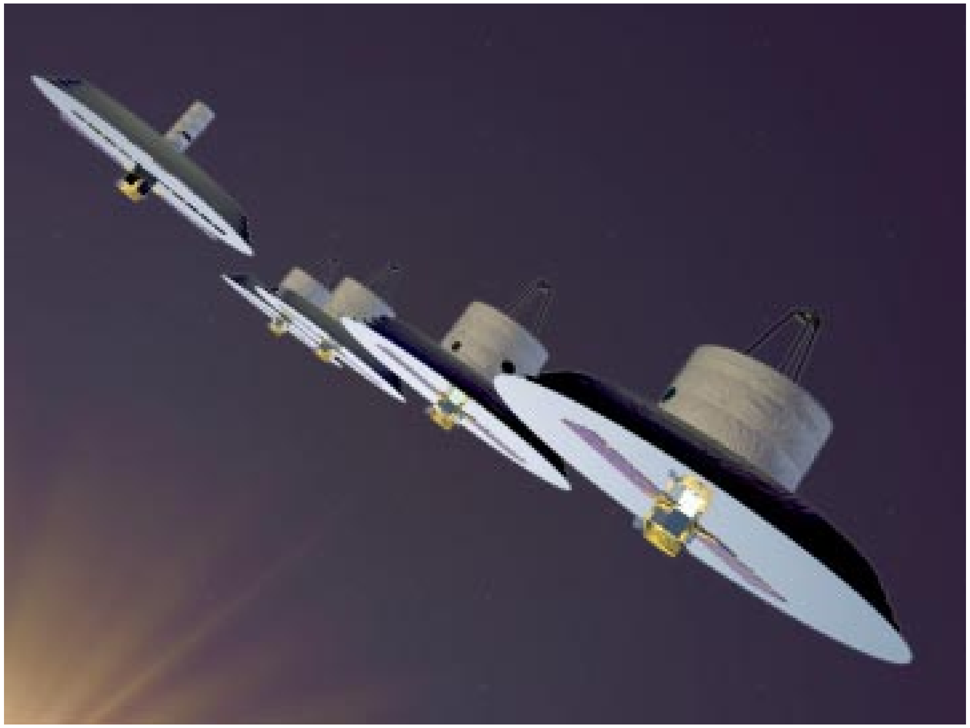
Terrestrial Planet Finder (TPF)

- Detecting light from planets beyond solar system is hard:
  - Planet emits few photons/sec/m^2 at 10 μm
  - Parent star emits 10^6 more
  - Planet within 1 AU of star
  - Dust in target solar system $\times$300 brighter than planet
- Finding a firefly next to a searchlight on a foggy night



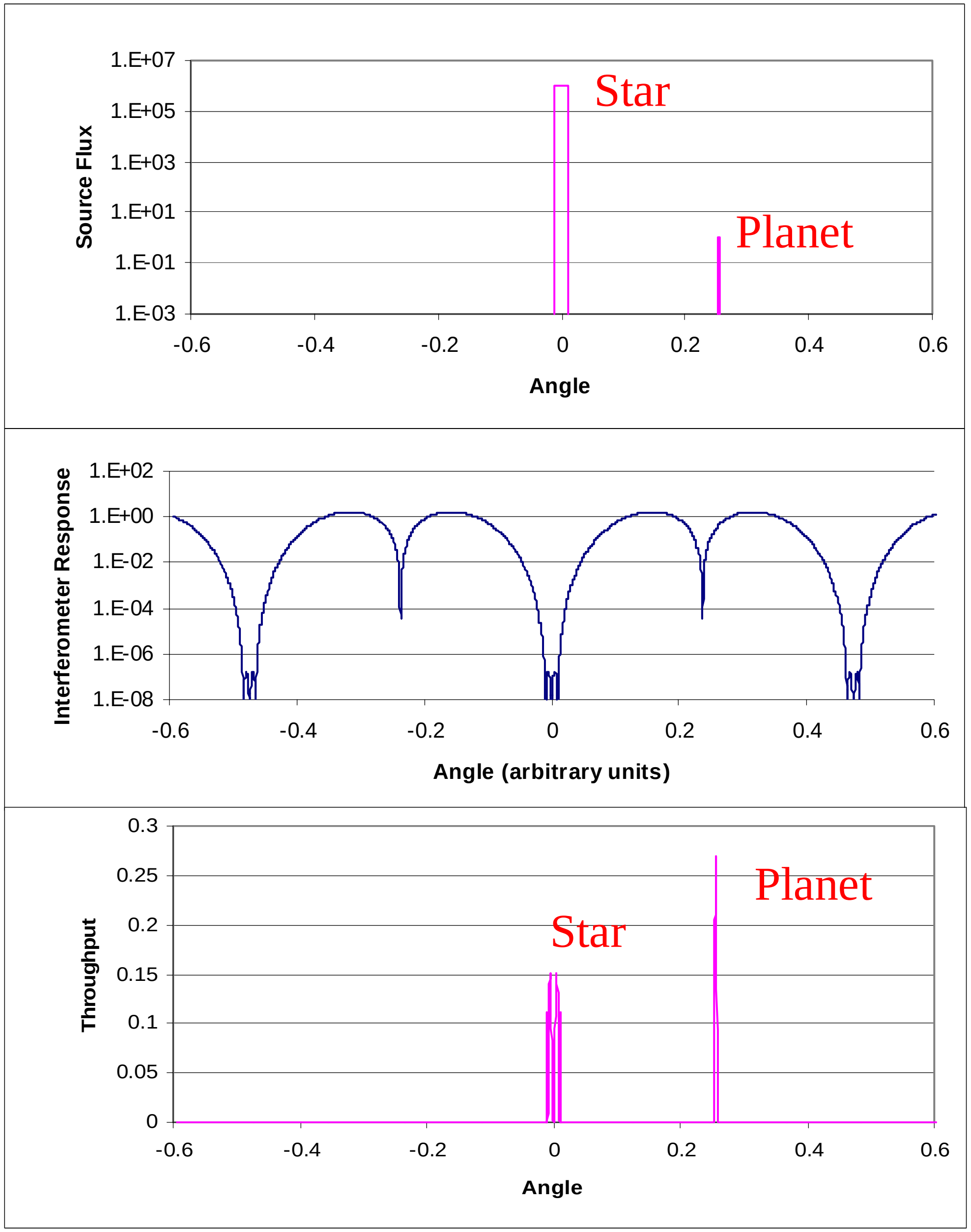
Illustrative TPF Concept

- IR interferometer with cooled 4x3.5 m mirrors and ~75-1000 m baseline
- Separated spacecraft for flexibility and full baseline coverage for general astrophysical imaging
  - <1 mas at 3 μm
  - Spectral Resolution 20-300
- Operate at 1 AU for 5 years with launch in 2011

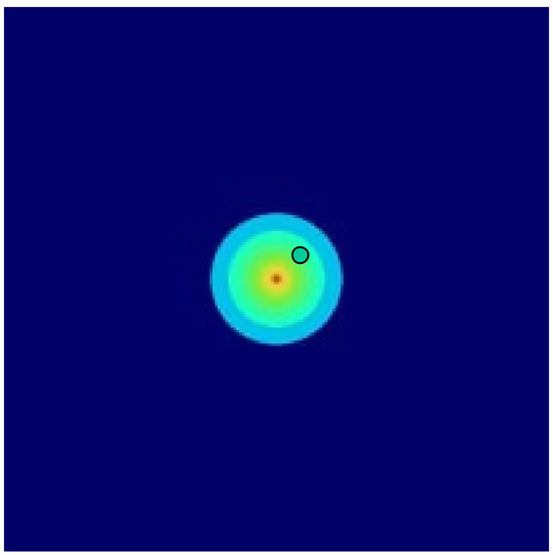


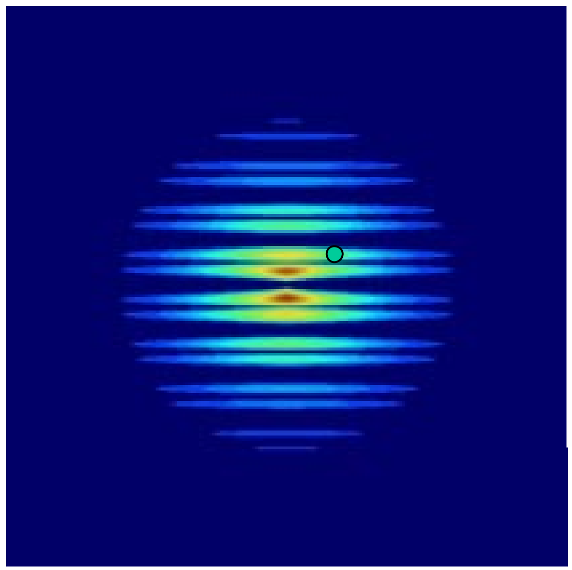
Nulling Interferometry: The Secret of Finding Terrestrial Planets

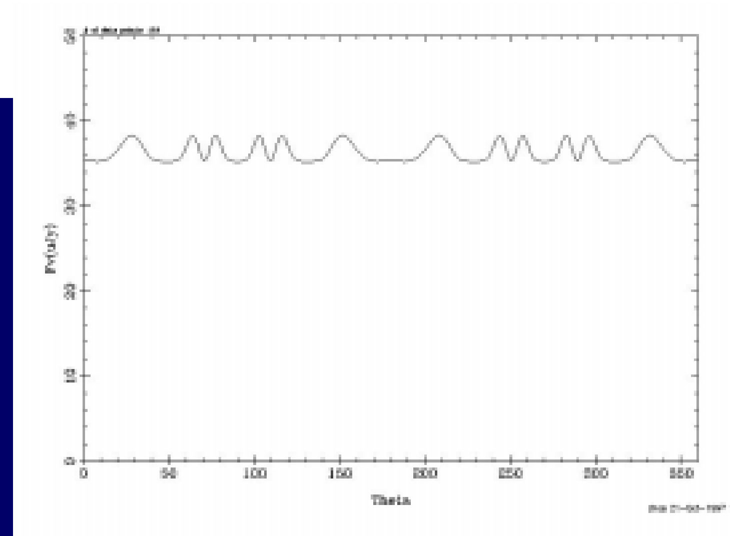
- Introduce π phase shift between 2 arms of interferometer
- Place star at on-axis null
- Planet sits off-axis and moves in and out of nulls as interferometer rotates around line-of-sight



TPF Builds Up Image Using Nulling



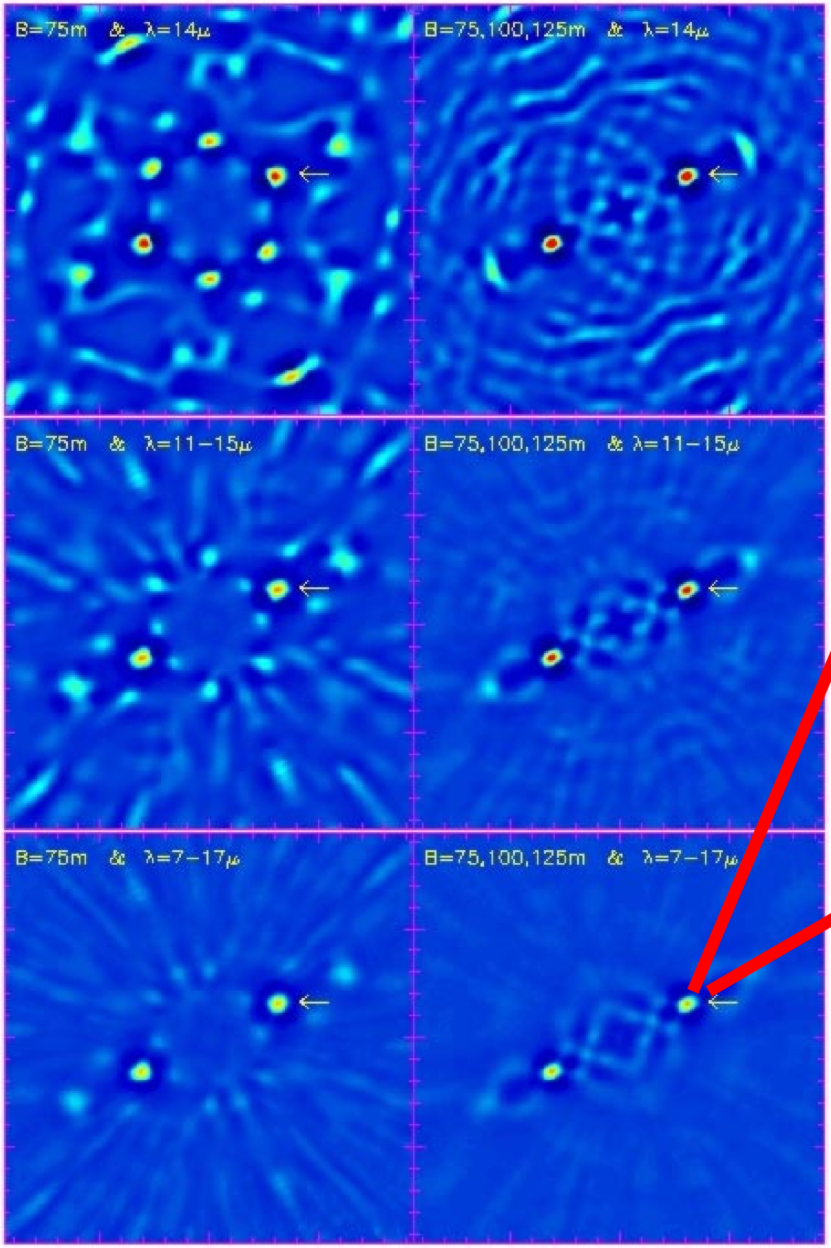




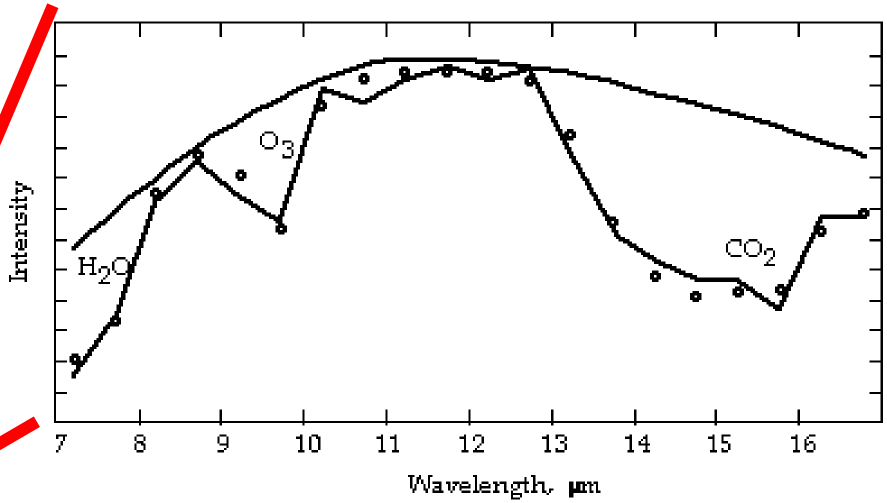
3. Time-series as TPF rotates

2. Target through TPF interference fringes

1. Simulated target

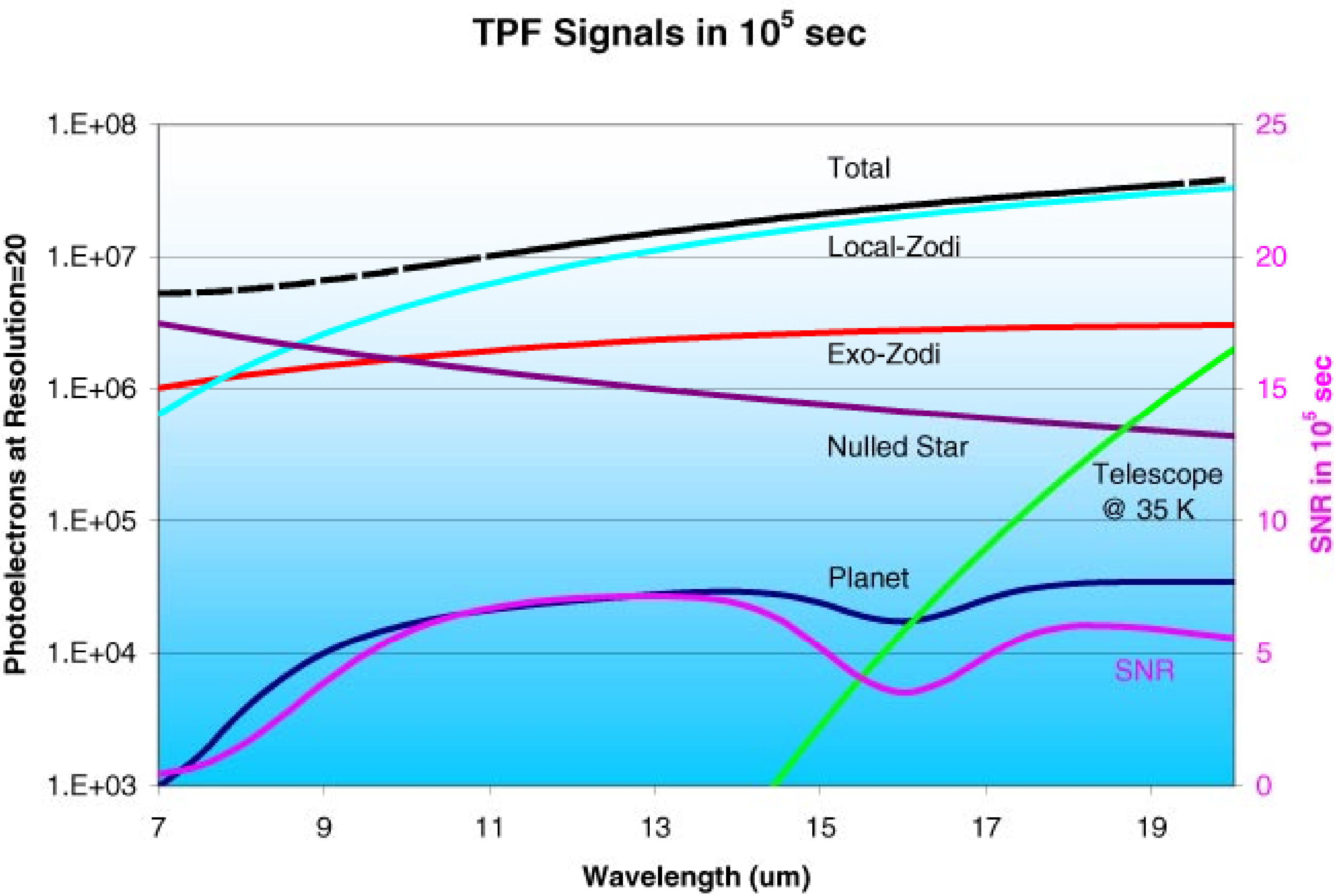


TPF Reconstructs Images and Spectra using Multiple Baselines and Wavelengths



5. Spectrum of planet

4. Reconstructed images

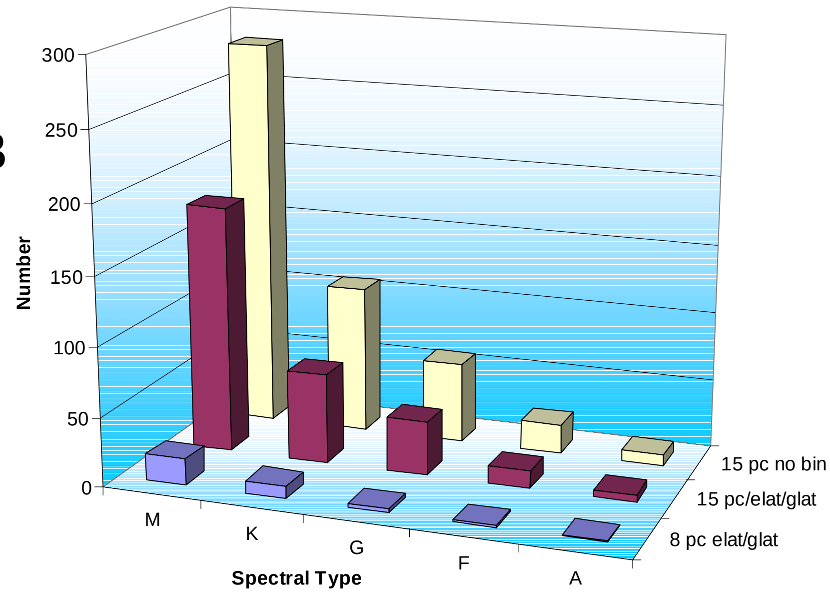

TPF Signals in 10^5 sec
Photoelectrons at Resolution=20
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
25
20
15
10
5
0
SNR in 10^5 sec
Total
Local-Zodi
Exo-Zodi
Nulled Star
Telescope
@ 35 K
Planet
SNR
7
9
11
13
15
17
19
Wavelength (um)

Observing Time Requirements for Planet Detection

Science Goal	12 μm Obs. of Earth at 10 pc	4x3.5m (1 AU)
Detect planet	Resl'n=3/SNR=5	2.0 hour
Detect atmosphere CO_2, H_2O	Resl'n=20/SNR=10	2.3 day
Is planet habitable? O_3, CH_4	Resl'n=20/SNR=25	15.1 day

TPF Planet Survey

- TPF will survey ~150 nearby stars based on SIM/Keck Census
  - 0.5-1 day per star repeated 2-3 times for confirmation and orbital information
- Follow-up brightest candidates with 2 week observations for sensitive spectroscopy looking for atmospheric signatures of habitability and even life

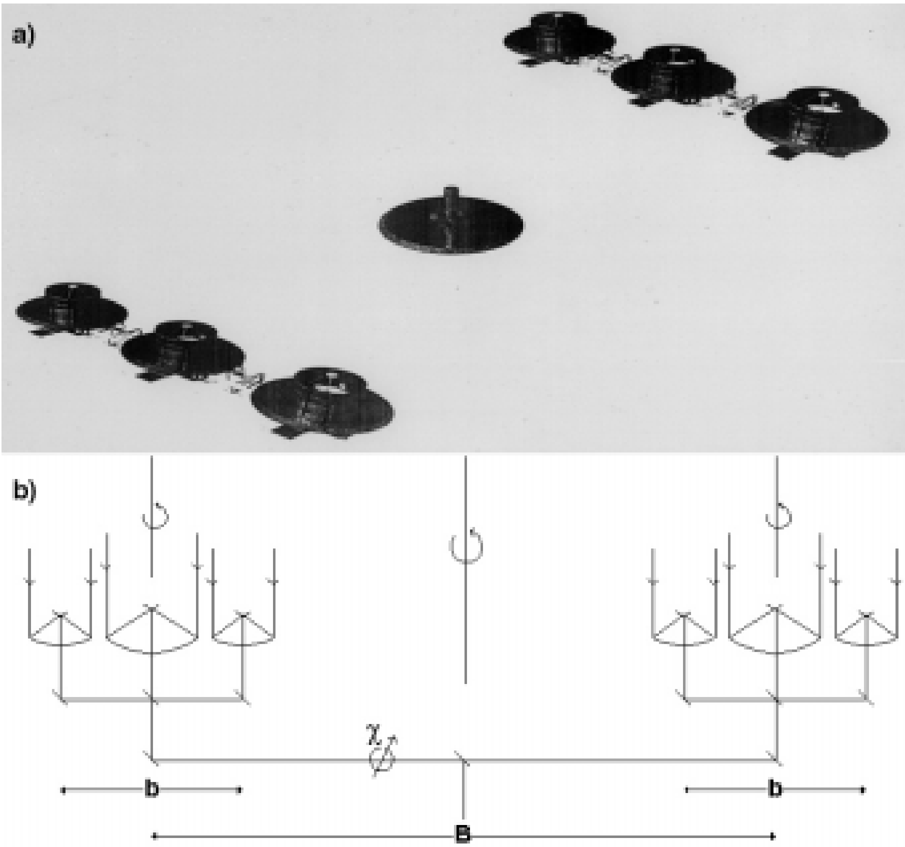


Nulling Configurations for TPF

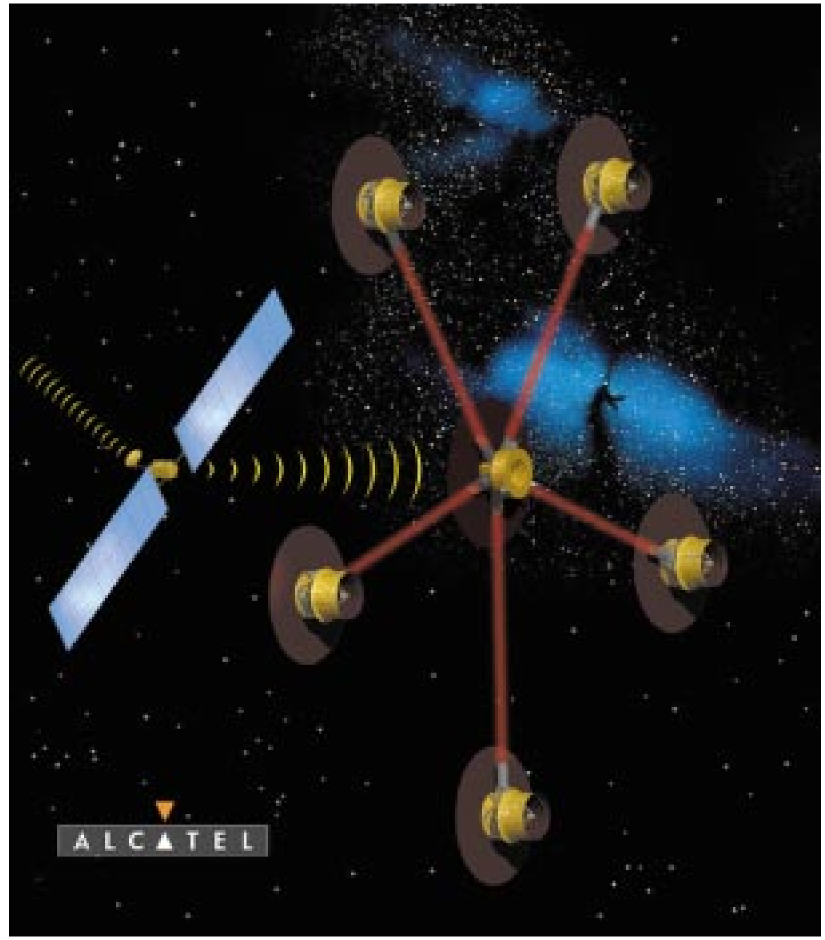
- Stellar leakage depends on angular diameter, interferometer baseline and configuration
  - 2 element (Bracewell) allows too much stellar leakage (θ^2 null)
  - 4-6 element systems can give broader (θ^6) null or narrower (θ^4) null with rapid temporal chopping, and better rejection of zodiacal dust
  - 2-D configurations such as Mariotti's can reduce requirement on array rotation
- Ability to tune null for each star using variable baseline reduces requirements on null

Number of telescopes	Array Configuration	Null Width	Chopping
4	Linear 1:2:2:1 or 1:3:3:1	θ^6	No
4	two 3-element interferometers	θ^4	Yes
4	Double Bracewell	θ^2	Yes
4	Angel Cross	θ^4	No
6	two fixed, 3-element interferometers on separated spacecraft	θ^4	Yes
6	ESA's *Mariotti* configuration	θ^4	Yes

Alternate TPF Configurations



Hybrid 6 element concept (Velusamy et al 1999) nulls star on small, fixed baseline. Provides phase information for improved imaging, zodi rejection.



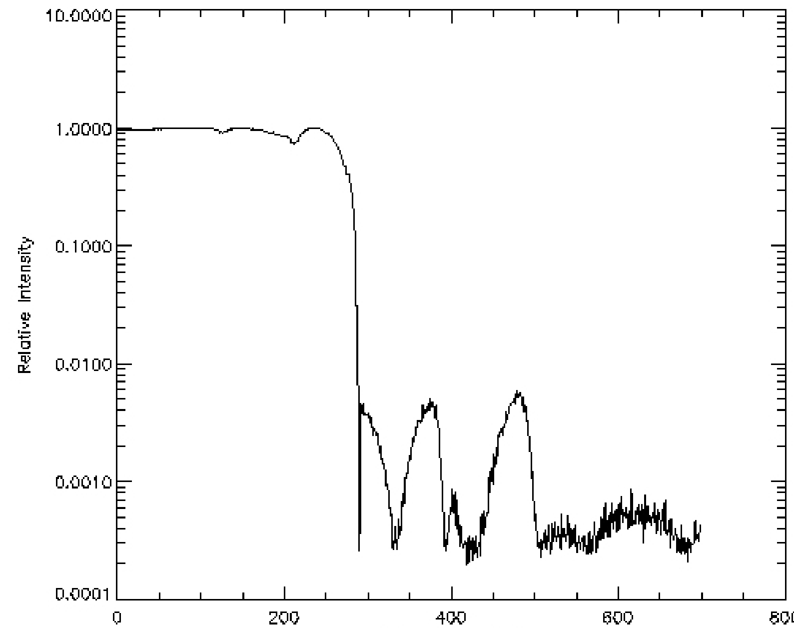
Mariotti concept for ESA's Darwin provides chopping, doesn't rotate.

Requirements for a Good Null

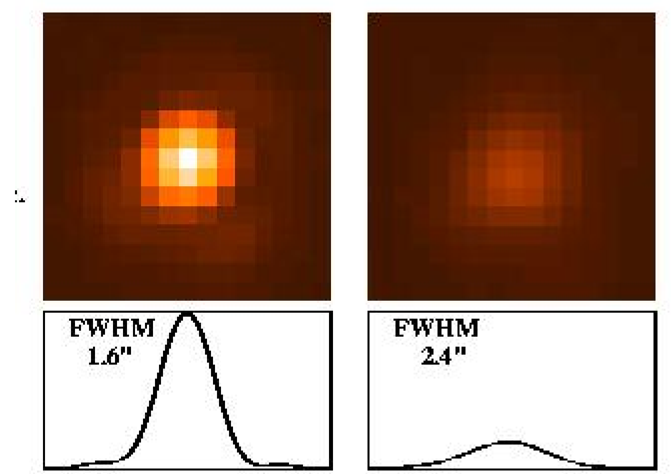
Error Source	*Constraint*	*Requirements for Null <10^{-6}@ 7μm; <$5x10^{-5}$@ 20 μm)*
Optical Path Errors	$\sigma_{OPD} < \lambda \sqrt{N} / \pi \sqrt{(1 + \sqrt{2})}$	3.5 nm 70 nm
Transmission Asymmetries between beams	$\sigma_{Inten}/I < 2\sqrt{N}$	<0.2% <1.4%
Pointing jitter	$\alpha < 0.8\ (\lambda/D)\ {}^{4}\sqrt{N}$	10 milli-arcsec 75 milli-arcsec
Differential Polarization Rotation	$\varphi < 2\sqrt{N}$	0.1 deg 0.7 deg
Differential polarization (s-p waves) Delay	$\Delta < 4\sqrt{N}$	0.2 deg 1.4 deg

Progress on Nulling

- University of Arizona and JPL working on interferometric nulling
  - Laser$\rightarrow$ white light
  - Optical $\rightarrow$ infrared
- Laboratory
  - ~10^4:1 for visible laser and R=20 diode (Serabyn)
- Telescope
  - 50:1 at MMT
- Requirements range from 10^{-4}-10^{-6} depending on wavelength, telescope size

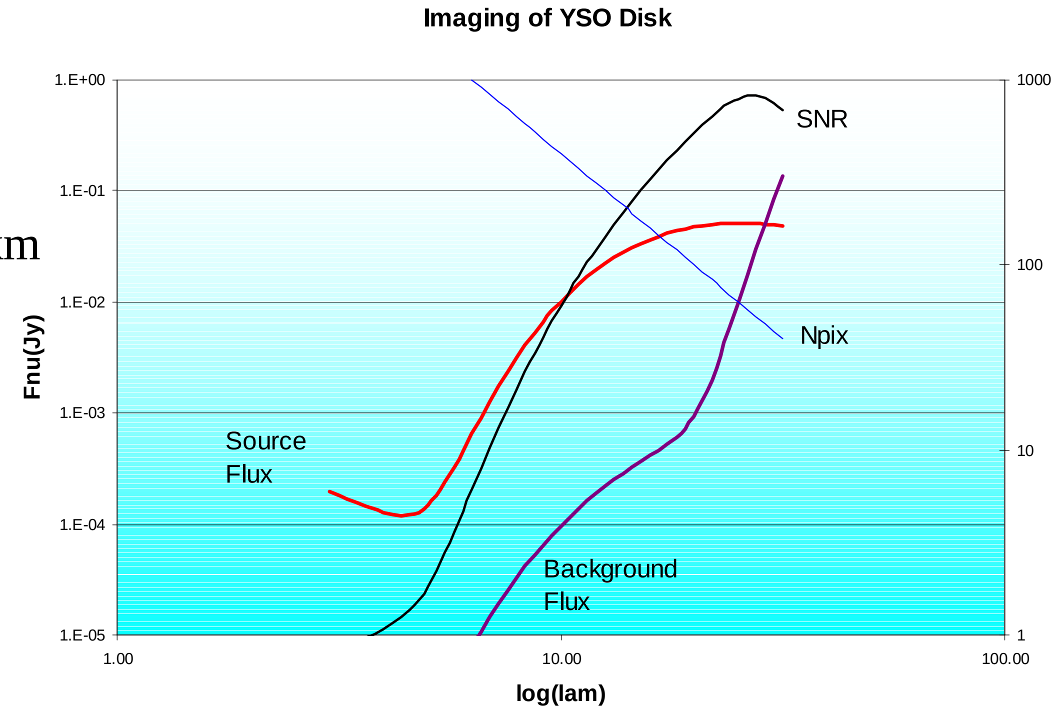


α Ori

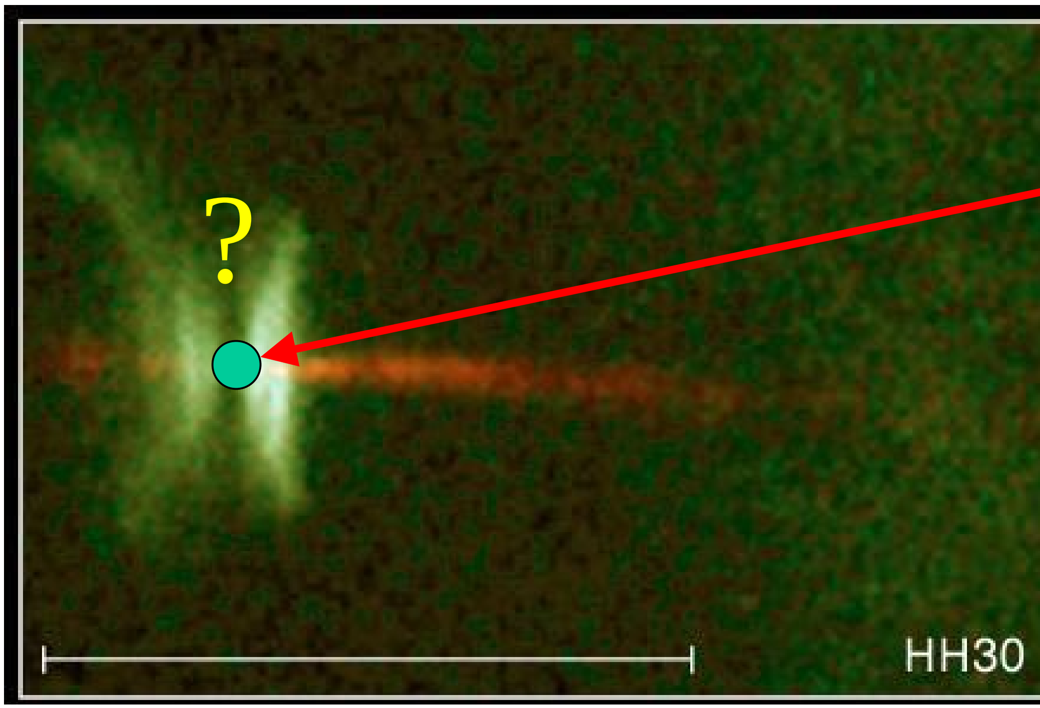


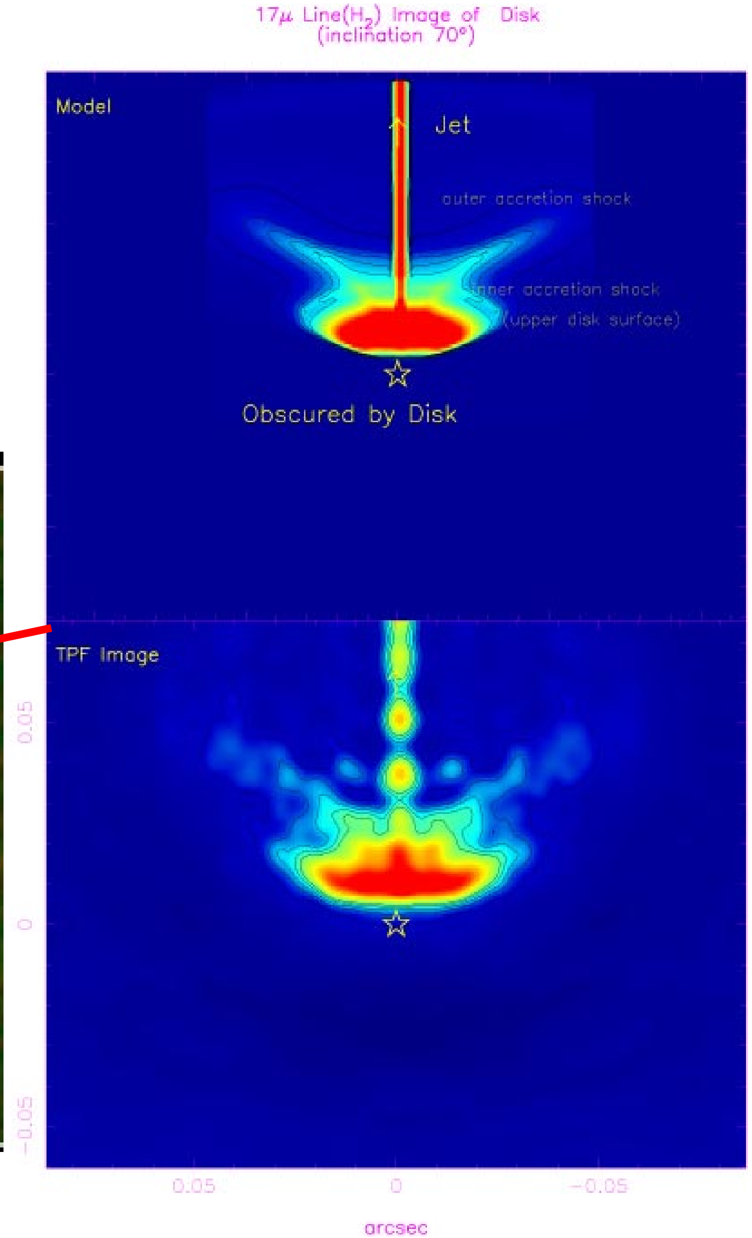
General Astrophysics with TPF

- TPF offers unprecedented resolution and sensitivity at 3-30 μm with R=5-300
  - resolution of <0.75 milli-arcsecond at 3 μm and 1 km
- Study star and planet formation with 0.1-1.0 AU resolution
  - Thermal and density structure
  - Composition of disks
  - Origin of Jets
  - Hot young planets in disks
- Probe obscured AGN cores

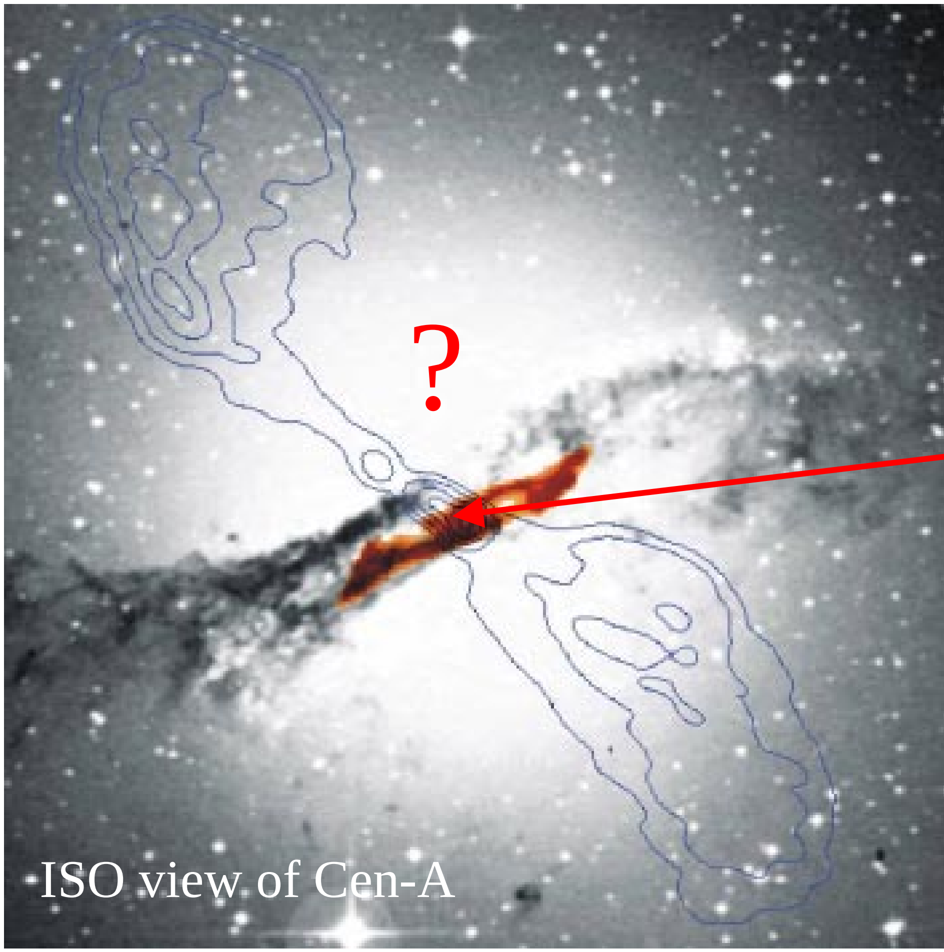


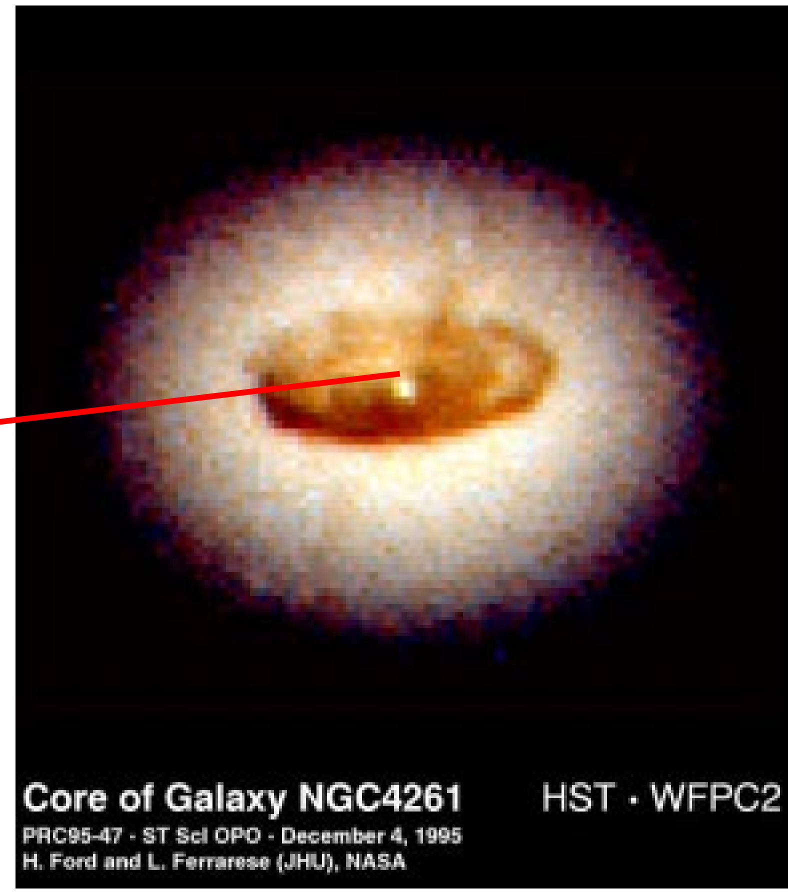
Disk and Jet Physics with TPF





Black Holes and AGN Cores



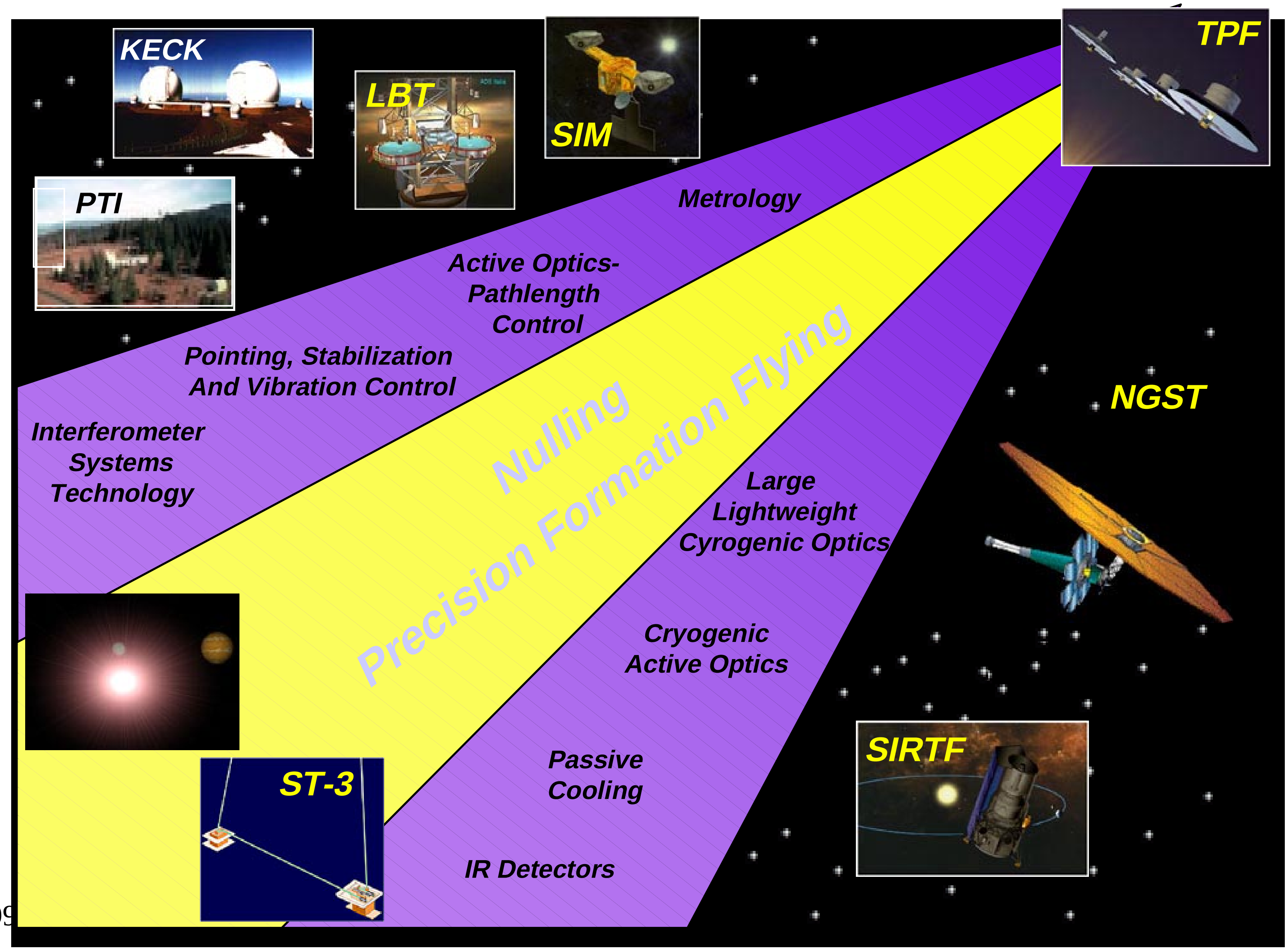


Dust Disk around Black Hole?

Origins Feeds Science and Technology Forward to TPF

Scientific and Technological Precursors to TPF		
Project	*Science*	*Technology*
Ground-based Interferometers: Keck Interferometer Large binocular Telescope (LBT) Very Large Telescope (VLTI)	Exo-zodiacal emission Planet census	Interferometry hardware & software Nulling Community training
Space Infrared Telescope Facility (SIRTF)	Exo-zodiacal emission Planetary companions	Passive cooling Drift away orbit IR detectors
Space Technology- 3 (ST-3)	---	Formation Flying Interferometer Operations
Space Interferometry Mission (SIM)	Planet census Exo-zodiacal emission	Interferometry hardware & software Nulling
Next Generation Space Telescope (NGST)	Exo-zodiacal emission Planetary companions	Lightweight optics Cryogenic actuators Active coolers

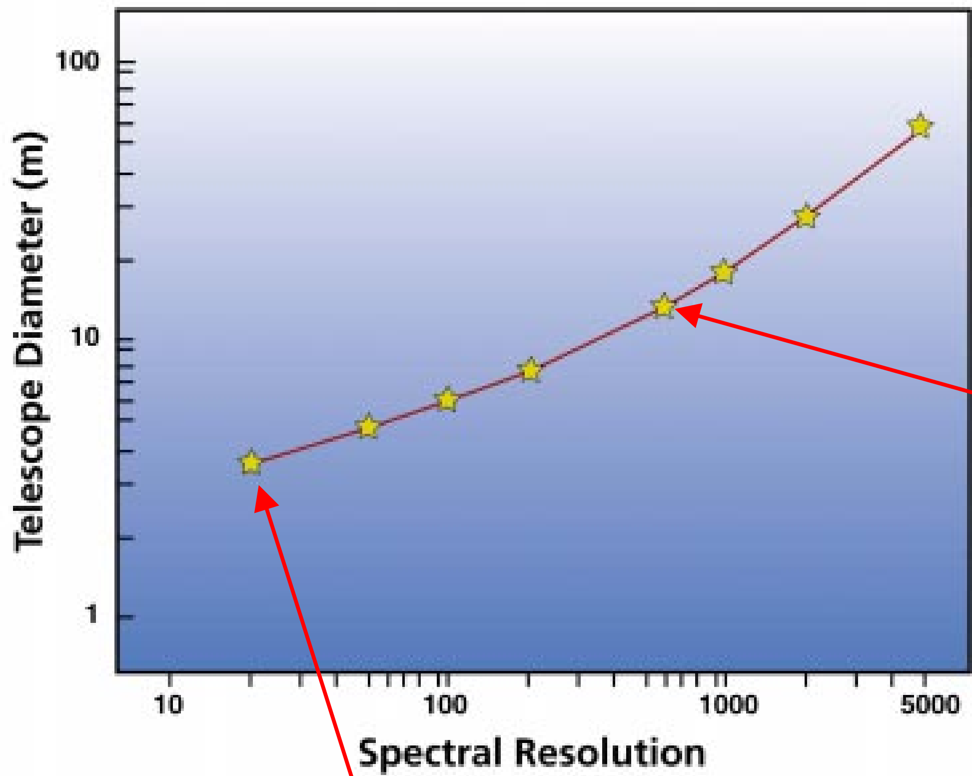
TPF Technology

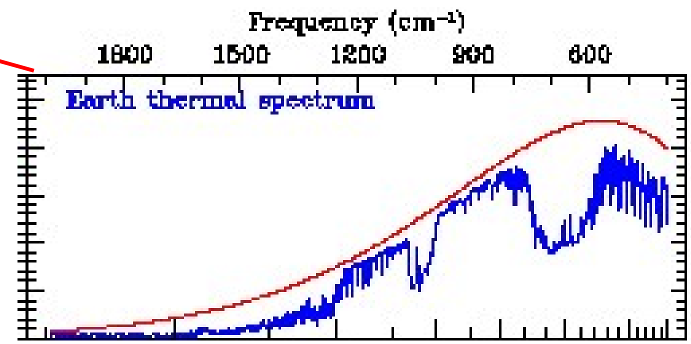


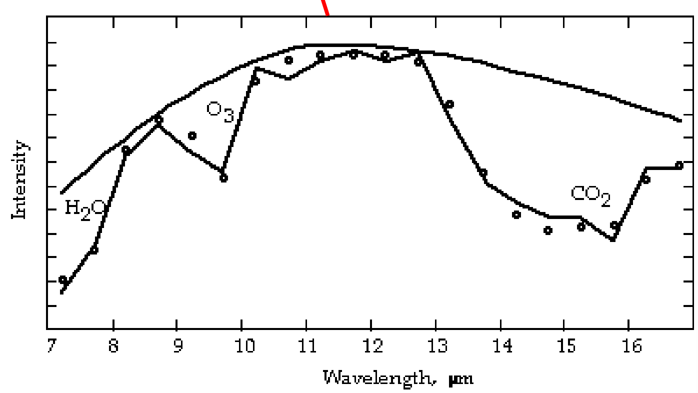
‘Origins’ Is a 25 Year Quest

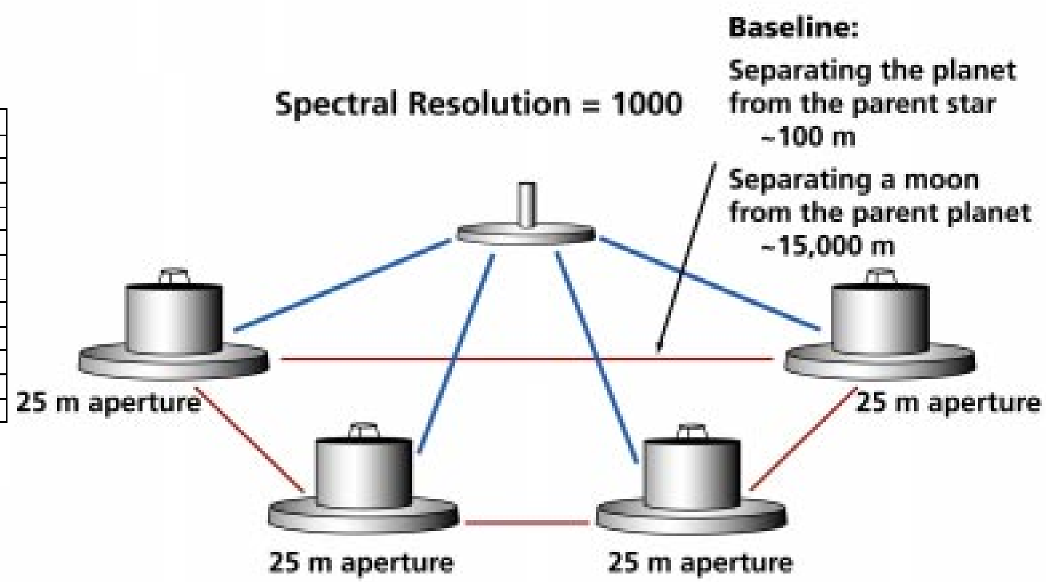
- Origins brings together physicists, astronomers, geologists and biologists to work on common goal of broad interest
- Technologies needed to answer these questions are daunting, but imaginable and therefore doable
  - *New ground-based and space-based observatories using interferometry and large (cryogenic) telescopes*
  - *When TPF is ready to start, technology will be in place*
- Requires long term commitment for technology development and missions
  - *NASA, OMB, White House and Congress have accepted Origins*
  - *Projects from now until 2015 (and beyond)*

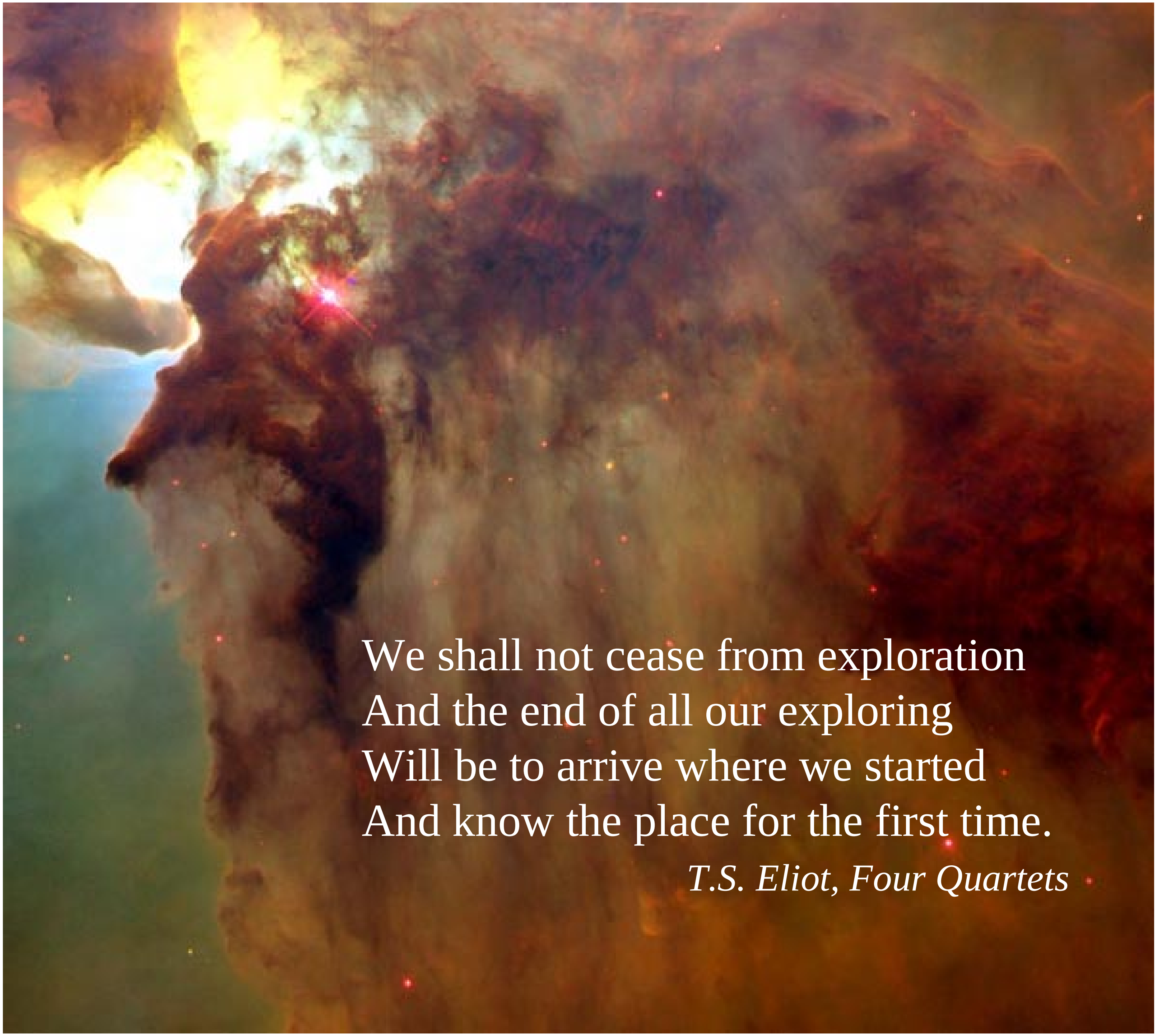
The Future: High Spatial or Spectral Resolution

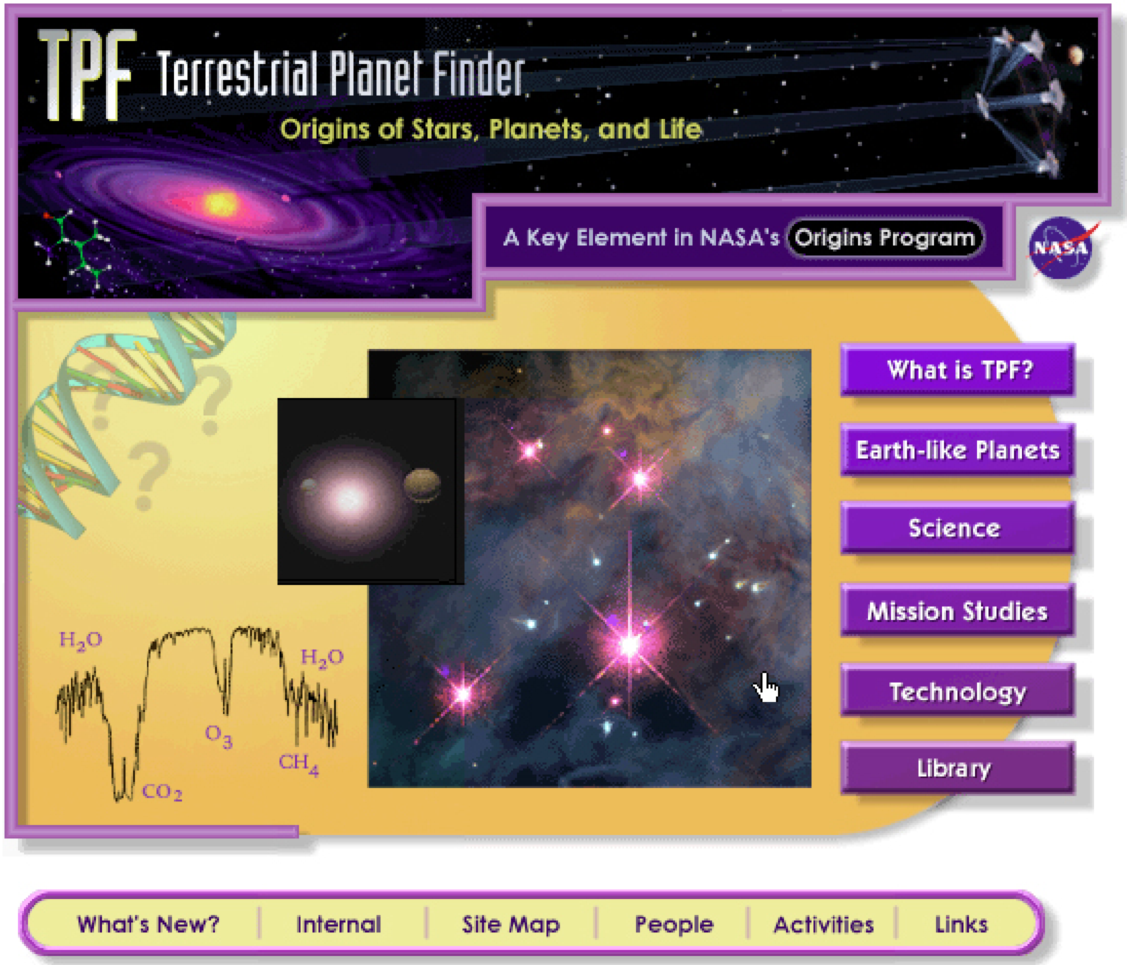









We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.
T.S. Eliot, Four Quartets



- For more information about the Terrestrial Planet Finder (TPF), check out our websites:
  - **http://tpf.jpl.nasa.gov**
  - **http://origins.jpl.nasa.gov**